Multidecadal Regime Shifts in U.S. Streamflow, Precipitation, and Temperature at the End of the Twentieth Century

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ABSTRACT

Intra- to multidecadal variation in annual streamflow, precipitation, and temperature over the continental United States are evaluated here through the calculation of Mann–Whitney *U* statistics over running-time windows of 6–30-yr duration. When this method is demonstrated on time series of nationally averaged annual precipitation and mean temperature during 1896–2001, it reveals that 8 of the 10 wettest years occurred during the last 29 yr of that 106-yr period, and 6 of the 10 warmest years during the last 16. Both of these results indicate highly significant departures from long-term stationarity in U.S. climate at the end of the twentieth century. The effects of increased wetness are primarily evident in the central and eastern United States, while evidence of warmth is found throughout the Rocky Mountain region and in the West. Analysis of annual streamflow records across the United States during 1939–98 shows broadly consistent effects. Initial evidence of the recent wet regime is most apparent in eastern streamflow, which shows a clear pattern of high-ranked mean annual values during the 1970s. Over the midwestern states, a coherent pattern of high-ranked annual flow is found during multidecadal periods beginning during the late 1960s and early 1970s and ending in either 1997 or 1998. During the late 1980s and early 1990s, a significant incidence of low-ranked annual flow conditions throughout the West was roughly coincident with the onset of western warmth during the mid-1980s. Evidence of highly significant transitions to wetter and warmer conditions nationally, and consistent variation in streamflow analyses, suggests that increased hydrological surplus in the central and eastern United States and increased hydrological deficit in the West may be representative of the initial stages of climate change over the continental United States.

1. Introduction

Previous work here surveyed intra- to multidecadal (IMD) variability in precipitation and temperature over the United States during 1932–99 through the calculation of Mann–Whitney *U* statistics over moving time windows of varying duration (Mauget 2003). That exhaustive analysis approach allowed for the objective and unguided identification of known features of low-frequency climate variability during that period, for example, the timing and the distribution of drought impacts during the 1930s and 1950s. In addition, the end of the twentieth century was marked as a period of significant wetness and warmth. Evidence of a recent wet–warm regime shift in U.S. climate, and modeling studies of the effects of elevated atmospheric CO_2 levels that suggest a drought-prone future in which evapotranspiration (E) dominates precipitation (P) (Manabe and Wetherald 1987; Rind et al. 1990; Gregory et al. 1997), lead to questions regarding the associated P–E balance of that regime shift. However, conclusions regarding that balance and the current drought vulnerability of U.S. climate cannot be drawn from independent analyses of temperature and precipitation. Here, in an effort to estimate the net hydrological effect of the recent shift to wetter and warmer conditions over the United States, the approach is to extend the general time series analysis method of Mauget (2003) to annual streamflow records over the period 1939–98.

Section 2 of this paper will describe the data used here in the analysis of annual U.S. streamflow, precipitation, and temperature. Section 3 will describe the analysis method of Mauget (2003), and will demonstrate that method via analyses of national average annual rainfall and temperature time series derived from U.S. climate division data. Section 4 will extend that analysis to time series of mean annual streamflow from gauge stations throughout the continental United States. Section 5 will provide summary and concluding remarks.

2. Data

Climate division data (Guttman and Quayle 1996) is derived from averages of monthly station data reported over the continental United States' 343 climate divisions, and, as used here, extends between January 1895 and September 2001. After 1930 divisional data values were derived via equal-weight averaging of monthly

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average temperature or cumulative precipitation reported from stations within each climate division. Before 1931 station data was not averaged over climate divisions, but was averaged statewide or regionally by the U.S. Department of Agriculture (USDA). Current pre-1931 climate division data values are inferred from those pre-1931 USDA averages and regression relationships between climate division and statewide averages calculated over the period 1931–82.

The streamflow data used here are drawn from the U.S. Geological Survey's (USGS) Hydro-Climatic Data Network (HCDN; Slack et al. 1993). These records consist of estimates of daily mean flow rates ($ft^3\ s^{-1}$) that are derived from subdaily measurements of stage (Rantz et al. 1982a,b). The mean annual (October–September) streamflow rates evaluated here were derived from reported monthly averages of daily rates. The gauging stations contributing to the HCDN were chosen based on the relative lack of anthropogenic time-dependent biases in the streamflow record; for example, biases due to the introduction of dams, diversions, or major land-use changes. The 167 stations considered here (Fig. 4a), were chosen based on the duration of their record, the effective area of their watershed regions, and the desire for a uniform coverage of watershed regions throughout the continental United States. Although HCDN data end in 1988, streamflow records used here were drawn from HCDN station records reported by the USGS's National Water Information System, which extend to 1998.

3. Running Mann–Whitney *Z* analysis and Monte Carlo methods

Low-frequency variation in the climate system might be considered as a central issue in climate analysis for a number of reasons. Defining the state of rainfall or temperature bias associated with an intra- to multidecadal climate mode, and predicting the duration of that mode, might provide the basis for climate forecasts several years in the future (Latif and Barnett 1996). With respect to the detection of climate change, evidence in the paleo-climatological record (Adams et al. 1999; National Research Council 2002), indicates that transitions to persisting climate shifts can occur over decadal timescales. This suggests that the consequences of increased atmospheric CO_2 levels may be as likely found in the relatively abrupt onset of IMD variation as in more gradual trendlike behavior. Finally, IMD climate variation may influence the simple definition of climate. That is, whereas climate normals are typically calculated over 30-yr periods, the dominance of one particular mode of IMD variability during those periods could produce biased statistics. As a result, the abnormally wet conditions reported both here and elsewhere (Karl et al. 1996) over the United States during the last 30 yr of the twentieth century would produce 1971–2000 normals that were wet compared to the climate of the twentieth century as a whole.

But in spite of the importance of low-frequency variation in the study of climate, most analysis methods are not well suited to identifying it in long-term data records. Although trend analysis has been frequently used to evaluate climate variation over the United States and North America during the twentieth century (e.g., Lettenmaier et al. 1994; Karl et al. 1993, 1995, 1996; Karl and Knight, 1998; Groisman and Easterling 1994; Kunkel et al. 1999; Groisman et al. 2001), low-frequency cyclic variation in the data can cause the significance or even the sign of trends to depend on the period over which trends are fitted. Fourier analysis can identify harmonic behavior, but implicitly assumes that it occurs more or less continuously over the entire period of record. Wavelet analysis (e.g., Lau and Weng 1995) detects intermittent harmonic variation by projecting wavelet transforms onto the data over moving time windows, but is still somewhat limited by the assumption that climate varies in an idealized cyclic manner. Even so, given the intermittent nature of climate variability, moving window methods such as wavelet analysis are relatively robust. The method used here follows the approach of wavelet analysis but makes more general assumptions about how low-frequency climate variability occurs; specifically, that such variability consists only of IMD climate regimes of arbitrary onset and duration within the period of analysis. These regimes are identified here through the calculation of Mann–Whitney *U* statistics over moving time windows of varying (6–30 yr duration. The derivation of Mann–Whitney *U* and *Z* statistics and an associated Monte Carlo protocol will be described through an analysis of spatially averaged annual rainfall over the continental United States.

Assuming an October–September water year, 106 yr of annual precipitation (apcp) totals can be derived for each climate division over the period January 1895–September 2001. Using those yearly totals and the areas of each climate division, a spatial average of national precipitation (NPCP) can be estimated:

$$\mathrm{NPCP}(\text{year } n) = \frac{\sum_{i=1}^{343} \mathrm{area}(i) \times \mathrm{apcp}(i, \text{ year } n)}{\sum_{i=1}^{343} \mathrm{area}(i)}. \quad (1)$$

The time series analysis approach used in Mauget (2003) and here evaluates the rankings of annual data values sampled from moving time windows. The test statistic used is the Mann–Whitney *U* statistic (Wilcoxon 1945; Mann and Whitney 1947; Mendenhall et al. 1990), which can be used to determine the significance of an arbitrary distribution of rankings in a sample. As used here, the formation of Mann–Whitney *U* statistics assumes the data have been ranked and divided into two classes. For example, the 106 yr of NPCP values in Fig. 1a might be ranked and divided into a class consisting of the sample being tested (class I, of, e.g., size n_I = 10) and the remaining nonsample rankings (class II, of

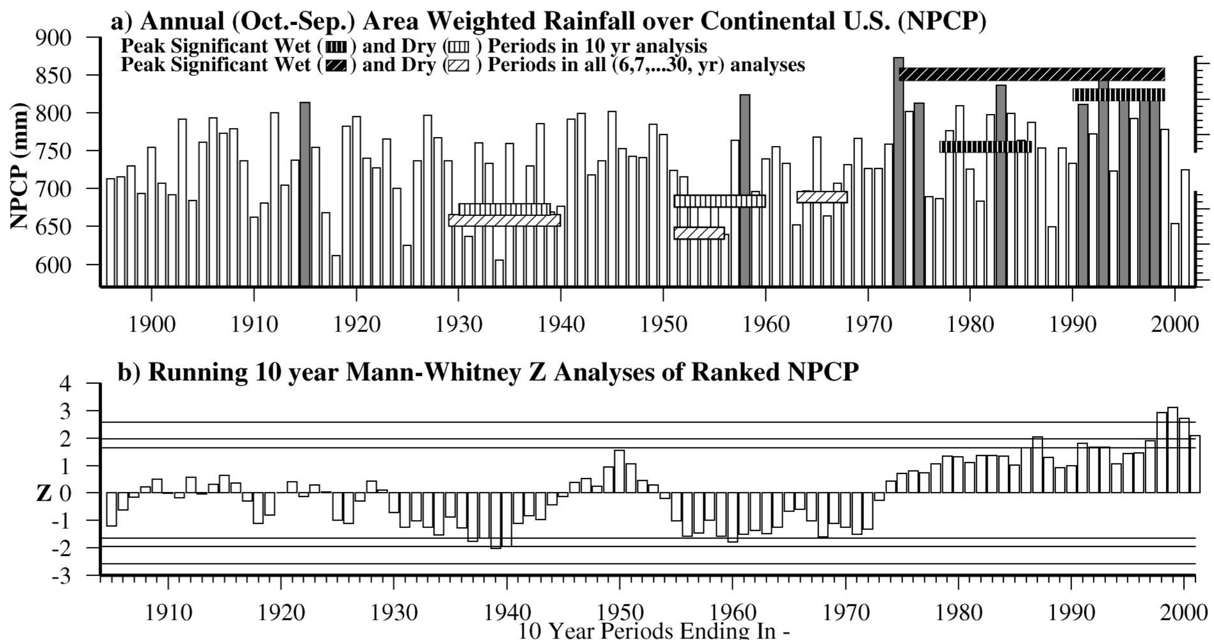

FIG. 1. (a) Time series of cumulative Oct–Sep rainfall spatially averaged over the 343 climate divisions of the coterminous United States (NPCP) for 1896–2001. Gray years mark the 10 most highly ranked NPCP values of 1896–2001. Vertically hatched horizontal bars show the 10-yr periods with the most significant incidence of high ($Z > 0$) and low NPCP rankings ($Z < 0$) identified by the running 10-yr analysis in (b). Oblique hatched horizontal bars indicate the periods with the most significant incidence of high and low rankings from running analyses using sampling periods of 6, 7, . . . , 30 yr. Vertical position of horizontal bars indicate Z values for rankings during those periods (right y axis). (b) Mann–Whitney Z statistics for running 10-yr samples of NPCP rankings. Horizontal lines indicate positive and negative significance at 90%, 95%, and 99% confidence levels.

size $n_{\mathrm{II}} = 106 - n_{\mathrm{I}}$). Although analytic expressions such as those found in Wilks (1995) and Mendenhall et al. (1990) are normally used to form sample U statistics, those values are equivalent to the total number of non-sample data values that precede each sample value when all data values are arranged by rank. That is, for the U statistic of the sample considered earlier (U_{I}):

$$U_{\mathrm{I}} = \sum_{i=1}^{n_{\mathrm{I}}} \sum_{j=1}^{n_{\mathrm{II}}} \varphi(\mathrm{Rank\ I}_i, \mathrm{Rank\ II}_j), \qquad (2)$$

where Rank I_i is the rank of the ith member of class I, etc., and $\varphi(\mathrm{Rank\ I}_i, \mathrm{Rank\ II}_j) = 1$ if Rank $\mathrm{I}_i <$ Rank II_j, 0 otherwise. Thus the maximum U_{I} statistic in this example would occur when that class accounts for the 10 highest rankings ($U_{\mathrm{I}} = 96 \times 10$), while the smallest statistic would result when it accounts for the 10 lowest ($U_{\mathrm{I}} = 0 \times 10$). More general sampling outcomes result in U statistics that are proportional to the incidence of high or low rankings in the sample, but bounded by those extreme values. Assuming that the 106!/96!10! possible sampling outcomes of class I rankings are equally probable, the resulting distribution of U_{I} statistics is Gaussian with a mean equal to the average of the maximum and minimum values [e.g., $\mu = 0.5 \times (10 \times 96)$], and a standard deviation given by the expression $\sigma = (n_{\mathrm{I}} n_{\mathrm{II}} \times (n_{\mathrm{I}} + n_{\mathrm{II}} + 1)/12)^{1/2}$ (Mann and Whitney 1947). These parameters can be used to Z-transform U statistics, with significantly high (low) Z values indicating a significant incidence of high (low) rankings in a sample relative to a null hypothesis that assumes random sampling. However, whereas climate variation can persist from year to year (Thiebaux and Zwiers 1984), Mann and Whitney's analytic solution for σ assumes that sampling outcomes consistent with both persistent and serially independent climate variation are equally probable. Given that sampling outcomes consistent with persistent, or "red," variation are more likely in a record of annual climate values, and that the associated persistence can vary with location, a more climate-specific null hypothesis will be posed here. Namely, that the precipitation, temperature, and streamflow records that are evaluated represent a stochastic climate sharing the same mean and variance of the actual climate record, and similar persistence characteristics, but are essentially stationary and unvarying over the period of analysis (H_0). From the standpoint of annual data rankings this is equivalent to assuming that high and low rankings are randomly distributed throughout time, but with persistence similar to that of the observed data. The parameters of U null distributions consistent with that hypothesis were derived here via the following Monte Carlo protocol:

1) Given a null hypothesis that assumes no long-term variation in the data, calculate AR(1), AR(2), and AR(3) regression coefficients from the autocorrelation values of the detrended data, and select the AR

model yielding the minimum Akaike Information Criteria score (Akaike 1974).
2) From the results of step 1, form autoregressive red noise processes.
3) Adjust the variance of the red noise process resulting from step (ii) and truncate the number of significant digits to agree with that of the data. Then, select red noise series of appropriate length—in the case of the NPCP series, 106—and rank those values.
4) From the ranked noise processes resulting from step 3 calculate appropriate null statistics, which in the current NPCP example would be U_I statistics derived from nonoverlapping 10-element segments of each red noise series.
5) Repeat steps 2–4 until 50 000 independent null realizations are calculated, and determine the distribution parameters of the resulting U_I null statistics.

Using the null distribution parameters derived from these Monte Carlo simulations (μ_{MC}, σ_{MC}), the Z statistics of samples of NPCP rankings can be used to test H_o:

$$Z = \frac{U - \mu_{MC}}{\sigma_{MC}}. \tag{3}$$

The resulting Mann–Whitney Z (MWZ) statistics for running 10-yr samples of ranked NPCP values can be found in Fig. 1b. In general, these running analyses can produce essentially redundant results. For example, when sampling running 10-yr periods through the 1930s the incidence of low-ranked NPCP values during both 1930–39 and 1931–40 are found to be significant at a 95% confidence level, although the former period is slightly more significant. As the goal is to isolate the most significant IMD variation occurring over distinct periods, the approach here is to identify only the most significant sequences of rankings exceeding a minimum 90% confidence threshold ($|Z| > 1.645$) and occurring over nonoverlapping time windows. Thus in Fig. 1a the distinct and optimally significant dry periods marked from the 10-yr analysis are 1930–39 ($Z = -2.015$) and 1951–60 ($Z = -1.781$). The significantly wet 10-yr periods identified are 1977–86 ($Z = 1.650$) and 1990–99 ($Z = 3.122$).

Because Mann–Whitney U statistics are evaluated over all possible 10-yr windows in the running analysis leading to Fig. 1b, nationally wet or dry periods occurring over any 10-yr time window can be identified during 1896–2001. That analysis was, however, restricted to the testing of 10-yr periods. To test for national rainfall regimes over a wider range of timescales, running calculations of U statistics were repeated using sample sizes of 6, 7, . . . , 30 yr. Varying sample size required that Eq. (2)'s μ_{MC} and σ_{MC} parameters be calculated for each window length, given the dependence of those parameters on sample size. Thus μ_{MC}–σ_{MC} parameter pairs were calculated independently for each of the 25 sample sizes during step 4 of the Monte Carlo simulations. After the running U statistics from each analysis were normalized by the appropriate null parameters [Eq. (3)] the Z statistics from all 25 tests that exceeded the minimum confidence threshold were, as in the 10-yr analysis, screened for those periods resulting in the greatest significance over distinct IMD periods. Thus the most significant negative Z statistic (-2.680) emerging from all 25 running analyses of NPCP rankings is found in the 6-yr analysis during 1951–56. This result effectively trumps the 1951–60 Z statistic from the 10-yr analysis and all other significant Z statistics from sampling periods that overlapped 1951–56. Similarly, the Z statistic from the 12-yr analysis during 1929–40 (-2.322) exceeds the 1930–39 statistic from the 10-yr analysis, and all other Z statistics that indicated dry conditions during the 1930s over other time windows. The most significant positive Z statistic (3.695) among all analyses, and the greatest magnitude Z statistic overall, is evident during the 27-yr period 1973–99.

The screening approach described earlier tests the significance of U statistics derived from annual rankings over running time windows, repeats those tests over a range of window lengths, then identifies the most significant sequences of high and low rankings occurring over distinct time windows. While this is an exhaustive testing approach, the method is also relatively objective in that the Mann–Whitney U statistic can detect such sequences, but imposes no arbitrary thresholds that define extreme rankings. As a result this process can objectively identify the onset and duration of the most significant IMD climate regimes during a particular analysis period.

The magnitude of the 1973–99 Z statistic for NPCP rankings allows for the rejection of the null hypothesis proposed earlier (H_o) and reveals a highly significant nonstationarity in U.S. rainfall during that time. A closer look at those rankings shows that that significance is in part due to the fact that 8 of the 10 most highly ranked years of 1896–2001 occurred during 1973–98 (Fig. 1a). This incidence of wet years in the last 29 yr of a 106-yr record suggests a shift in U.S. climate more fundamental than that of normal IMD climate variation. If the statistics of U.S. rainfall were essentially stationary during the past century, as H_o assumes, those wet years would be more randomly distributed throughout the 1896–2001 water years. The probability of finding this specific incidence of wet years in a 29-yr sample drawn from a stationary 106-yr population could be estimated using a hypergeometric probability distribution (Mendenhall et al. 1990). However, classical hypergeometric statistics would assume that each year's ranking was statistically independent from the preceding and following year, while IMD climate variation will reduce the number of temporal degrees of freedom in a climate record of annual values. A better estimate of the significance of the occurrence of "top 10" wet years in Fig. 1a could be derived using Monte Carlo–generated

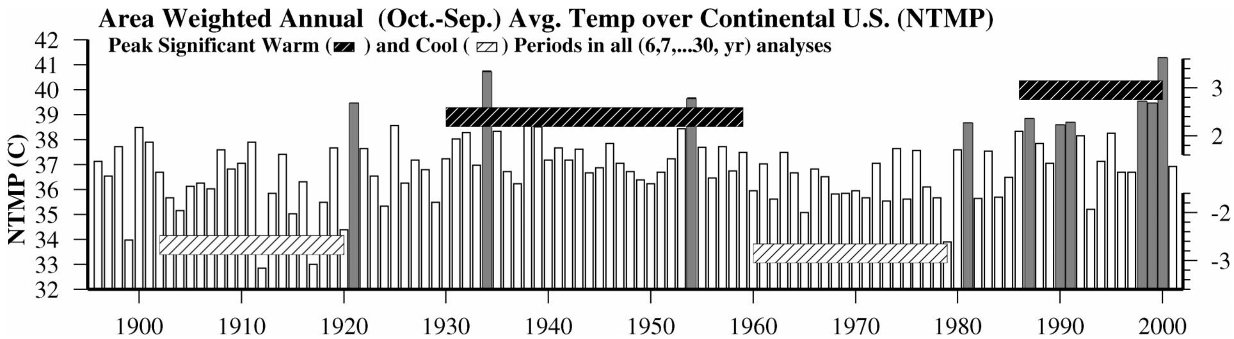

FIG. 2. As in Fig. 1a for average annual (Oct–Sep) temperature spatially averaged over the counterminous United States (NTMP) for 1896–2001. Oblique hatched horizontal bars mark periods with the most significant incidence of high ($Z > 0$) and low NTMP rankings ($Z < 0$) from running analyses similar to that in Fig. 1a using sampling periods of 6, 7, . . . , 30 yr.

null distributions. Such distributions were formed here via the previously described Monte Carlo protocol, with one modification. That is, that during the calculation of null statistics in step (v), the number of the 10 most highly ranked values found in nonoverlapping 29-yr sequences of each red noise series was noted. In two separate repetitions of this protocol, eight or more top 10 values were found in those sequences on 54 occasions; that is, 54 times out of 100 000 null realizations. That result and the Z statistic for NPCP rankings during 1973–99 are not independent, as both test for the incidence of extreme rankings during that period. One test examines the incidence of specific high rankings, the other the general incidence of high rankings. But both tests allow for the rejection of a hypothesis of long-term stationarity at a 99.9% confidence level. While Karl et al. (1996) have assigned an approximate 90% confidence level to the increase in average annual U.S. rainfall after 1970, the incidence of highly ranked NPCP values found here and in Mauget (2003) after 1972 indicates a more significant departure from stationary national rainfall conditions.

An analysis identical to that leading to Fig. 1a but conducted on a time series of nationally averaged October–September mean temperature (NTMP) can be found in Fig. 2. The peak significant cool and warm IMD climate periods evident in the NTMP U statistics show a low-frequency cycle in national temperature during 1896–2001, with 1902–20 and 1960–79 indicated as cool periods, and 1930–59 and 1986–2000 as warm periods. The most significant statistic overall ($Z = 2.938$) results from the incidence of highly ranked warm years during 1986–2000. Like the NPCP time series in Fig 1a, a high incidence of top 10 warm years are also found during the final years of the 106-yr NTMP record, with 6 of the 10 warmest years nationally occurring during 1986–2000. As in the earlier NPCP example, the probability that 6 of the 10 warmest years in a stationary 106-yr record would occur during a 15-yr period was tested here using a Monte Carlo–generated hypergeometric null distribution. In two separate repetitions of that modified Monte Carlo protocol, six or more top 10 values were found in 15-yr red noise sequences in 131 of 100 000 null realizations. As a result, both that test and the 1986–2000 NTMP Z statistic show a nonstationarity in late-century U.S. temperature at a 99% confidence level.

To show where the current wet and warm climate regime is most apparent over the continental United States, the Mann–Whitney Z statistics for October–September rainfall rankings during 1973–99 and temperature rankings during 1986–2000 are plotted in Figs. 3a and 3b at the climate division level. The corresponding U statistics were derived from annual rankings for each climate division during both of those periods, and those statistics were then Z-transformed using μ_{MC}–σ_{MC} parameter pairs generated for each climate division's rainfall and temperature record at the appropriate sampling size. That is, $n_I = 27$ yr for the annual rainfall records and $n_I = 15$ yr for the temperature records. In those figures the most significant IMD effects are found over more or less distinct regions, with wet conditions evident in southwestern, southern, midwestern, and northeastern climate divisions, and warm conditions most apparent over the western United States.

4. Mann–Whitney Z analyses of annual streamflow records

The preceding analysis shows that the final decades of the twentieth century were significantly warm and wet over the continental United States as a whole, and that those respective effects were most evident west and east of the Rocky Mountains. However, a shift to warmer and wetter climate conditions might lead to distinctly different climate outcomes, depending on the resulting balance between precipitation (P) and evapotranspiration (E). The net transfer of water between the earth's surface and the atmosphere is determined by the P–E balance, and over land areas that transfer makes itself apparent in related changes in soil moisture (w_s), groundwater, that is, lake, reservoir and aquifer levels (w_g), and streamflow (R):

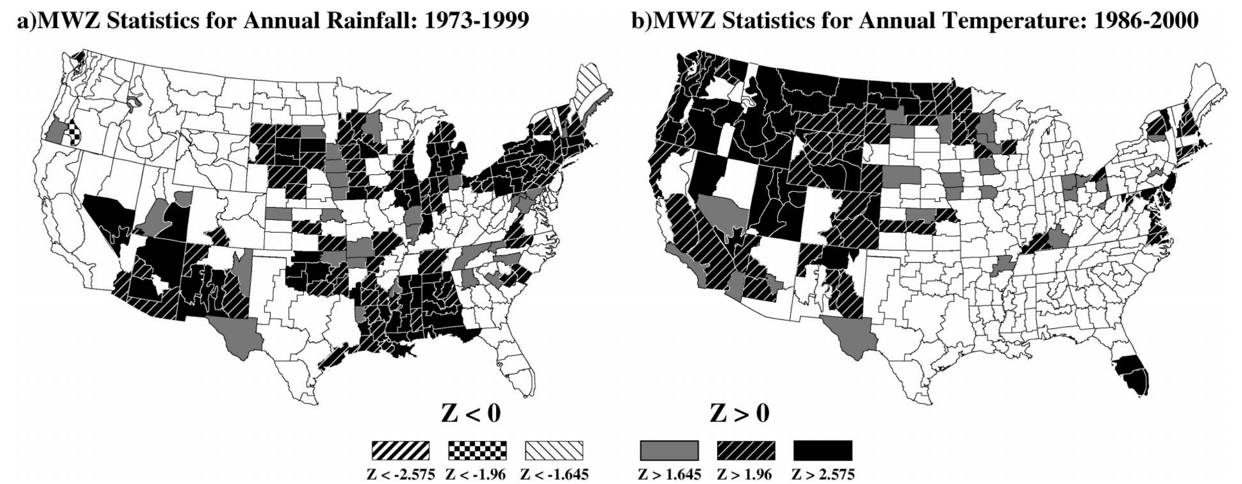

FIG. 3. (a) Mann–Whitney Z statistics for annual rainfall rankings at the climate division level during 1973–99. Positive and negative Z statistics significant at 90%, 95%, and 99% confidence levels are marked as in the bottom legend. Significant positive (negative) Z statistics indicate a significant incidence of high (low) annual rainfall rankings during those periods. (b) As in (a) for mean annual temperature rankings at the climate division level during 1986–2000.

$$P - E = R + \frac{\partial}{\partial t}w_s + \frac{\partial}{\partial t}w_g. \tag{4}$$

Dividing each term in Eq. (4) into climatological means and time-varying components results in a climatological balance equation,

$$\overline{P} - \overline{E} = \overline{R}, \tag{5}$$

and a balance equation describing the variation of anomalies about that climatology,

$$P' - E' = R' + \frac{\partial}{\partial t}w'_s + \frac{\partial}{\partial t}w'_g. \tag{6}$$

Over watershed regions that support nonzero annual streamflow values in the mean ($\overline{R} > 0$) the net climatological flux of moisture into the watershed's surface is also positive ($\overline{P} - \overline{E} > 0$). Under a wet–warm climate regime shift ($P' > 0$, $E' > 0$) the total moisture flux might decrease below ($P' - E' < 0$) or rise above ($P' - E' > 0$) that climatology. In the former case the net increase in evaporative loss from the surface would deplete soil and free-standing surface moisture and decrease watershed runoff. In the latter case soil moisture, groundwater, and streamflow levels would tend to rise above the long-term average. Thus a shift to wetter and warmer conditions could conceivably lead to either a drying or a moistening of the surface relative to climatology, depending upon whether increased precipitation or temperature effects are dominant. Evidence from modeling studies suggests that large-scale deficits in soil moisture, in addition to being a consequence of climate variability, might also cause dry conditions to persist through one of two mechanisms. Some studies have shown that soil moisture deficits can reduce precipitation through the reduction of surface evapotranspiration (Shukla and Mintz 1982; Fennesy and Shukla 1999; Hong and Kalnay 2002). Others suggest an influence on the dynamics of the overlying atmosphere. The results of Wolfson et al. (1987), Oglesby and Erickson (1989), and Atlas et al. (1993) show that reduced soil moisture leads to an increase in the Bowen ratio, lowered surface pressure, and increased geopotential heights over North American regions. If those effects occurred over a large enough area, the resulting atmospheric geopotential anomaly could distort the overlying moisture advection patterns over a similar spatial scale. Both mechanisms have the potential for acting in a positive feedback mode by reducing or diverting rainfall once large-scale soil moisture deficits have been established. The existence of a low-frequency climate regime in which evapotranspiration tends to exceed precipitation suggests that such feedbacks could be influential over similar timescales, and also suggests an associated risk for long-term drought and desertification.

Given the potential for dry surface conditions to maintain an anomalously dry climate, an important question to explore is how the recent wet–warm climate regime has affected surface moisture. That issue is addressed here through an analysis of Mann–Whitney U statistics of mean October–September streamflow during the 60-yr period 1939–98. By acting as a spatial integrator of the state of watershed runoff, streamflow provides an indirect measure of an area's P–E balance and soil and surface moisture tendency throughout that watershed. As annual mean runoff anomalies and the associated surface moisture tendency are generally constrained to be of the same sign in the absence of anthropogenic effects such as irrigation, the qualitative state of surface moisture during IMD periods marked by anomalous annual streamflow might also be inferred. Thus significant IMD sequences of highly ranked annual flow conditions might mark an increase in the P–E balance above climatology, and wetter soil moisture and ground water conditions. Conversely, significant sequences of low-ranked annual flow would reflect a shift towards a decreased transfer of water into the earth's surface and increasing surface aridity.

In evaluating mean annual streamflow during 1939–98, the same running analysis method used to identify significant sequences of NPCP and NTMP rankings in Figs. 1a and 2 was used. The only departure from those earlier examples was that of the shorter duration of the annual streamflow records and those aspects of the Monte Carlo process (i.e., step 3) that depend on record length. Like those examples, the running analyses of each streamflow time series were repeated using sample sizes between 6 and 30 yr, and the null hypothesis tested was that of long-term stationarity (H_o). These tests were conducted on the streamflow records from 167 HCDN gauge stations located across the continental United States in six regions (Fig. 4a). In Fig. 4a the southeastern region is color-coded beige, the northeastern region violet, the midwestern region yellow, the south-central region red, the Intermountain west region blue, and the western region, green. In Fig. 4b the optimally significant IMD periods of high-ranked and low-ranked annual streamflow found in the course of those running analyses are marked at 90($|Z| > 1.645$), 95($|Z| > 1.96$), and 99%($|Z| > 2.575$) confidence levels, and are plotted against backgrounds shaded according to the station's regional location in Fig. 4a. The green and red vertical lines in Fig. 4b mark the onset years of the late-century wet (1973) and warm (1986) regimes identified in Figs. 1a and 2. The following discussion will describe the major patterns of significant IMD streamflow variability evident over Fig. 4a's six regions.

In Fig. 4b a clear pattern of high-ranked annual streamflow conditions is apparent over the southeastern and northeastern regions during the 1970s. Throughout the results for stations 1–62 these conditions are evident in significant Z statistics over time windows that generally begin during the years 1971–73 and end during the years 1979–81. The coincidence of the onset of this decadal high-flow regime with the beginning of the 1973–99 national wet regime of Fig. 1a suggests that that rainfall transition was initially most evident in the eastern United States. Of the 62 gauge stations in those eastern regions, 18 also show multidecadal high-flow periods extending from the early 1970s to either 1997 or 1998 (e.g., stations 9, 11, 13, 33, 34, 44, 45, 52, 55, 60). Other stations showing high-flow conditions in the southeastern region during the 1970s also show high-flow conditions resuming during the late 1980s and early 1990s (e.g., stations 15, 16, 21–23). However, stations 25–28 also show periods of significant high flow between the late-1950s and the 1980s.

Relative to the two eastern regions, a more coherent pattern of high-ranked annual flow during late-century multidecadal periods is evident over the midwestern region (stations 63–97). Stations 63–80 are situated in the eastern and central portions of an agriculturally important region known as the Corn Belt. Of those 18 gauge stations, 12 (stations 63, 66–68, 70–73, 75, 76, 78, 80) show a significant incidence of high-ranked annual flow during periods beginning during the late 1960s and early 1970s and ending in either 1997 or 1998. In the climatologically drier western portion of the Corn Belt a shift to higher annual flow rates appears to lag flow rates evident at stations farther to the east. Stations 81–83 show a significant occurrence of high-ranked flow after the early 1980s, while farther to the west and north stations 85–88 show significantly high annual rates during 1993–98. But while most Corn Belt stations show evidence of higher annual flow conditions during recent decades, the results from midwestern stations farther to the north (stations 89–91, 94–96) show periods of significant low flow during the 1980s and 1990s.

Over the south-central region (stations 98–112) stations 102 and 104 show a significant incidence of high annual flow conditions during 1973–97. The fact that these stations in the state of Missouri are adjacent to the central Corn Belt region (stations 75–77) suggests that these high-flow periods are part of the same multidecadal high-flow regime found in the records of stations 70–80 during that same time. Although many stations in the south-central region show evidence of higher-flow conditions during recent decades, three stations in west Texas and southern New Mexico (stations 108, 112, 113) show evidence of a shift to lower-flow conditions.

Evidence for significant IMD streamflow regimes over the Intermountain region is mixed after the late 1970s. While stations in the states of New Mexico (114–117), Arizona (128–130), and Colorado (118) show high-flow periods of varying duration after that time, other stations in Colorado, Montana, and Utah (stations 120–127) experienced low-flow periods during the late 1980s and early 1990s. The latter evidence of dry conditions in the central Rockies appears more clearly in the annual flow time series of western gauge stations. Among the 34 stations in the western region (stations 134–167), 24 (stations 134–152, 154–157, 159) experienced a significant incidence of low-ranked flow conditions during time windows beginning in 1987. Other stations (i.e., stations 153, 158, 160, 161, 167) show the onset of dry conditions in 1985. Those low-flow conditions end in either 1992 or 1994. As a result, it would appear that roughly coincident with the beginning of a late-century national warm period (Fig. 2), which was most evident in western climate divisions (Fig. 3b), there also occurred a period of drought (Bell and Basist 1994) and low annual streamflow conditions throughout the western and parts of the intermountain regions. Another pattern of common streamflow variation in the western region, but over a multidecadal period and of opposite sign, is apparent in northwestern gauge stations between the late 1940s and the mid-1970s. Fourteen stations in northern California (stations 148–150),

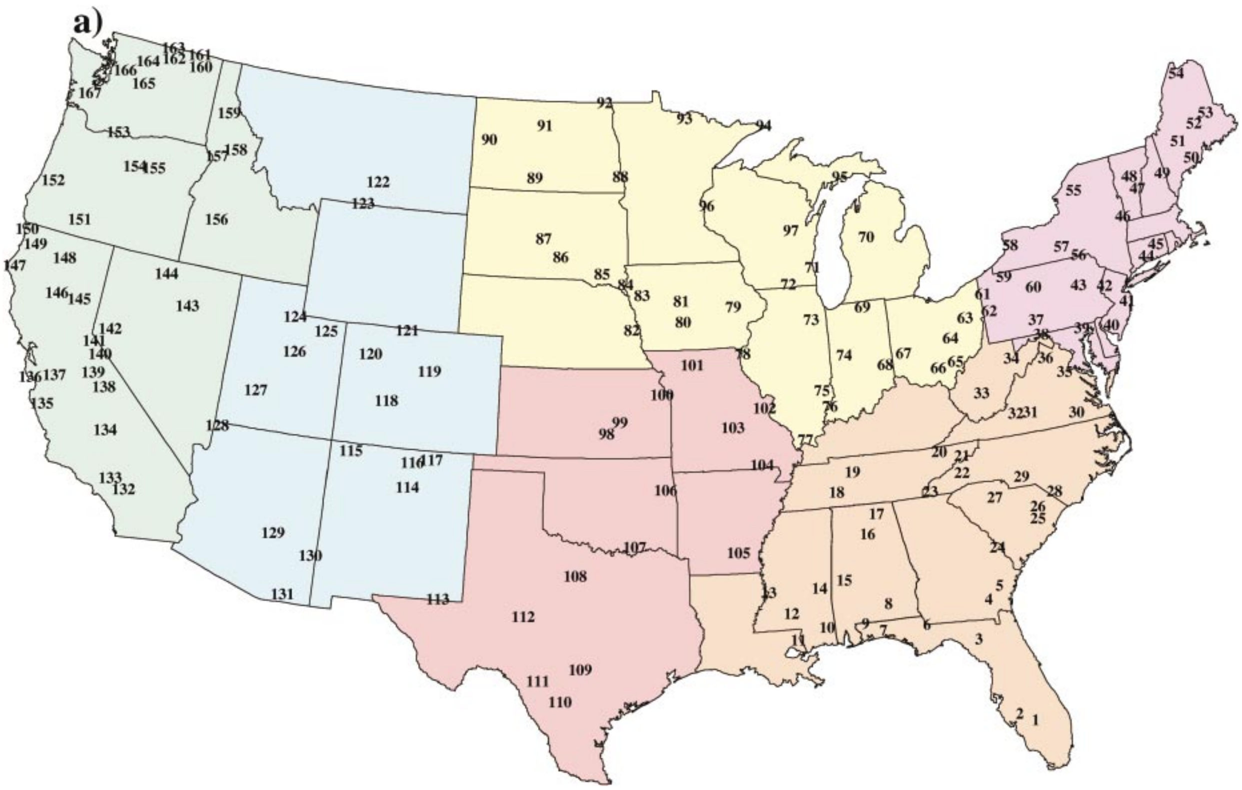

FIG. 4. (a) Locations of the 167 Hydro-Climatic Data Network (HCDN) streamflow stations evaluated. (b) Horizontal bars indicate the optimally significant periods of high and low annual flow conditions indicated by running Mann–Whitney Z analyses over 6-, 7-, . . . , 30-yr time windows during 1939–98, for each station mapped in (a). Background shading indicates regional location of station as shaded in (a). Positive and negative Z statistics significant at 90%, 95%, and 99% confidence levels are marked as in the legend at top. The green (red) vertical line indicates the beginning of the 1973 (1986) water year, which marks the onset of nationally wet (warm) conditions in Fig. 1a (Fig. 2).

Oregon (stations 151, 152), Idaho (stations 157–159), and Washington (stations 153, 163–167) show the onset of high-flow conditions that begin between 1946 and 1951, and end during the period 1972–77. This long-term shift to higher annual streamflow closely coincides with a period of higher streamflow and salmon production in the Pacific Northwest identified by Mantua et al. (1997), which they attribute to a multidecadal oscillation in northern Pacific climate referred to as the Pacific decadal oscillation (PDO).

The close agreement in the phase and duration of Pacific Northwest streamflow regimes found here with the results of Mantua et al. supports the idea that that high-flow period was linked to low-frequency variation in northern Pacific climate. But although the early 1970s saw the end of high-flow conditions in the northwest, that period also marked the onset of high-flow conditions in the midwestern and eastern United States. This indicates, circumstantially, that the general roots of that transition to wetter conditions east of the Rockies may be tied to the current phase of the PDO, which many (Trenberth 1990; Zhang et al. 1997; Minobe 1997; Nakamura et al. 1997; Mantua et al. 1997) suggest began in 1976/77. But here, the most identifiable break point in IMD climate variation over the continental United States in Fig. 4b would appear to be earlier in the 1970s. Before the 1973 water year—the wettest year of 1896–2001 over the continental United States, as measured by NPCP rankings—the predominant pattern of IMD streamflow in Fig. 4b is that of high-flow conditions in the Pacific Northwest, and relatively low-flow conditions in the Midwest and eastern United States. After that year, that general pattern appears to reverse with the appearance of high flow east of the Rockies and periods of low-flow conditions in the west.

5. Summary and conclusions

Intra- to multidecadal (IMD) regimes in time series of annual U.S. precipitation (Fig. 1a) and mean temperature (Fig. 2) during 1896–2001, and in annual mean streamflow records during 1939–98 (Fig. 4b), were identified here through Mann–Whitney U statistics derived from annual rankings sampled over running time windows. As the magnitude of U statistics are proportional to the incidence of high or low rankings during a sampling period, such running analyses can identify the most statistically significant sequences of extreme

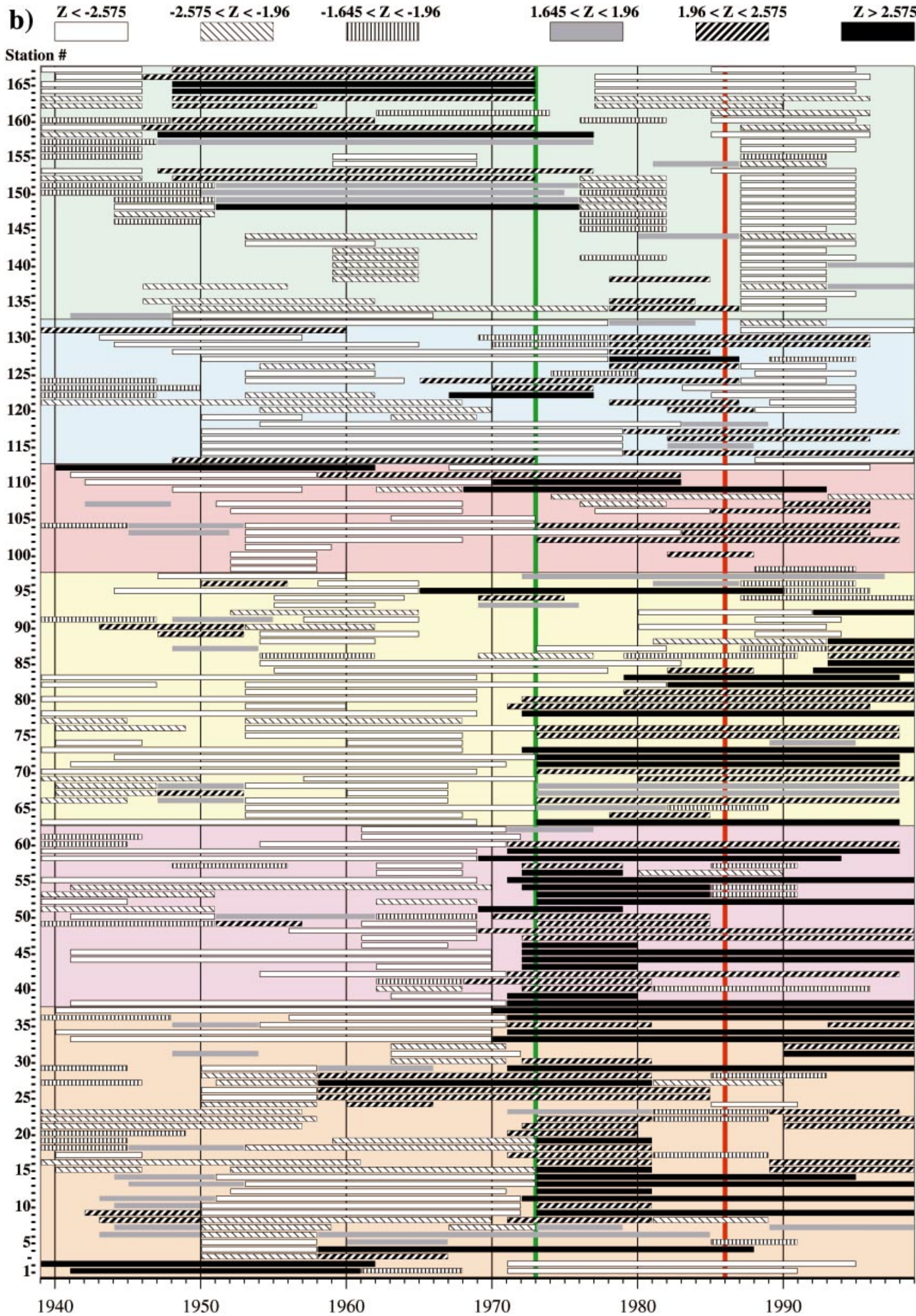

FIG. 4. (*Continued*)

annual rankings in a data record at a fixed sample size. Repeating these analyses over a range of sample sizes—here, 6–30 yr—allows for the identification of climate regimes of arbitrary onset and duration in the data record. The significant IMD variation found here in U.S. precipitation, temperature, and streamflow include:

- A distinct nonstationarity in U.S. rainfall after 1972. In the national precipitation time series, 1973–99 is indicated as the period with the most significant incidence of high-ranked annual rainfall averaged over the continental United States, including 8 of the 10 wettest years of 1896–2001. Relative to a null hypothesis that assumes stationarity in U.S. annual rainfall over that 106-yr record, the magnitude of the associated Mann–Whitney Z statistic (3.694) indicates that that hypothesis can be rejected at a 99.9% confidence level after 1972. These wet conditions are most clearly expressed in the southwestern, central, and eastern United States (Fig. 3a).
- A comparable nonstationarity in U.S. temperature after 1985. Running analyses of U statistics of nationally averaged annual temperature (Fig. 2) showed the most significant incidence of nationally warm years to occur over 1986–2000, during which 6 of the 10 warmest years of 1896–2001 were found. Given a null hypothesis of long-term stationarity in U.S. temperature, the general incidence of high-ranked warm years during that 15-yr period allows for the rejection of that hypothesis at a 99% confidence level. These warm conditions are most evident in the western and Intermountain regions of the United States (Fig. 3b).
- Late-century variation in annual streamflow that is generally consistent with that found in the precipitation and temperature analyses. While the final decades of the twentieth century saw significant wetness but less evidence of significant warmth in the central and eastern United States, a significant incidence of high-ranked annual flow conditions over IMD timescales is also found in those regions. These conditions are most apparent in high-flow conditions throughout the east during the 1970s, and in multidecadal periods of high flow in the Midwest after the early 1970s. In the West, where the predominant evidence is that of increased warmth, the most consistent and widespread variation in streamflow were low-flow conditions during the late 1980s and early 1990s.

The analysis here of average U.S. precipitation and temperature over the past century shows significant late-century departures from an idealized stationary climate. That is, a hypothetical climate with the general statistical traits of actual climate, but essentially random and unchanging in the long term. Recent and significant departures from that null climate may indicate either natural or anthropogenic, that is, greenhouse gas (GHG) related, climate variability. But although the emphasis here has been on the analysis of historical data with no consideration of causal roots, the timing and nature of the recent variation in U.S. temperature and precipitation does suggest the effects of increasing GHG concentrations. The onset of nationally warm years evident here after 1986 is concurrent with a similar warming transition in the spatially averaged global temperature record (Folland et al. 2001; Jones and Moberg 2003), which suggests it may be a North American expression of a global climate effect. Some suggest that this recent warming may be primarily due to the effects of higher GHG concentrations. Tett et al.'s (1999) integrations of coupled atmosphere–ocean general circulation models driven by various combinations of natural and anthropogenic radiative forcing indicate that while increasing solar irradiance may have contributed to warming during the early twentieth century, CO_2 warming effects are dominant after the mid-1970's. Similarly, Lean et al. (1995) and Lean and Rind (1998) estimate that anomalous solar forcing may have contributed to approximately one-half of the observed 0.55°C global surface warming since 1900, but only one third of the 0.35°C warming since 1970. The highly significant regime shift to increased U.S. precipitation found here during the early 1970s is also consistent with the strengthened hydrological cycle expected to accompany greenhouse warming (Cubasch et al. 2001; National Assessment Synthesis Team 2000; Trenberth 1999). Although positive rainfall trends are evident over other land surface areas during the twentieth century (Folland et al. 2001), determining whether similar regime shifts are apparent over regions outside of the continental United States would require extending the current analysis to more global climate records. Even so, given the marked shift to nationally warm and wet conditions in the closing decades of the twentieth century and the consistency of that shift with likely GHG-related effects, an interesting possibility to consider is that the first consequences of greenhouse warming—augmented by the effects of increased solar irradiance—are already apparent over the continental United States.

Assuming the possibility that recent wet and warm conditions over the United States might mark the early effects of climate change, an important issue to consider is the associated balance between precipitation and evapotranspiration. Where anomalous evapotranspiration is dominant, these changes may mark a transition to a more drought-prone climate. Conversely, a shift to a relatively drought-resistant climate might be suggested in those areas where increased precipitation and runoff is apparent. Here, IMD streamflow regimes are used as indirect proxies for the anomalous P–E balance over the associated watershed region, and the inferred balances in recent years appear to differ east and west of the 100th meridian. Throughout the midwestern, southeastern, and northeastern regions in Fig. 4b the widespread evidence of a multidecadal shift to higher annual streamflow values after the early 1970s is consistent with the general dominance of precipitation during that time. Thus, east of the 100th meridian (~gauge stations

1–114 in Figs. 4a,b), the common evidence of increased precipitation and streamflow over multidecadal periods indicates a shift to wetter surface conditions. Given the relatively recent onset of warm conditions over the West, the coincidence between that post-1985 warming and subsequent low-streamflow conditions during the late 1980s and early 1990s may be more circumstantial. However, that coincidence does suggest a shift to a climate dominated by temperature anomalies, and a possible tendency to increased aridity in the more arid western regions. As a result, if the recent significant shifts in precipitation and temperature mark the first effects of climate change over the United States, it appears those effects might be amplifying the most general feature of national climate. That is, that change has led to wetter conditions east of the 100th meridian, and drier conditions to the west.

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